High-energy scattering and locality: gravity and strings

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Based on:

hep-th/0604072;
hep-th/0703116;
arXiv:0705.1816, w. Gross and Maharana;
arXiv:0705.2197;
WIP w/ M. Gary; D. Marolf; M. Srednicki

One of the cornerstones of Quantum Field Theory is locality

Yet, we suspect not strictly valid.

Some reasons:

BH information paradox (most acceptable resolution)

(e.g. holography - rather extreme form)

Hints from strings: extendedness; AdS/CFT

Expected breakdown of classical spacetime

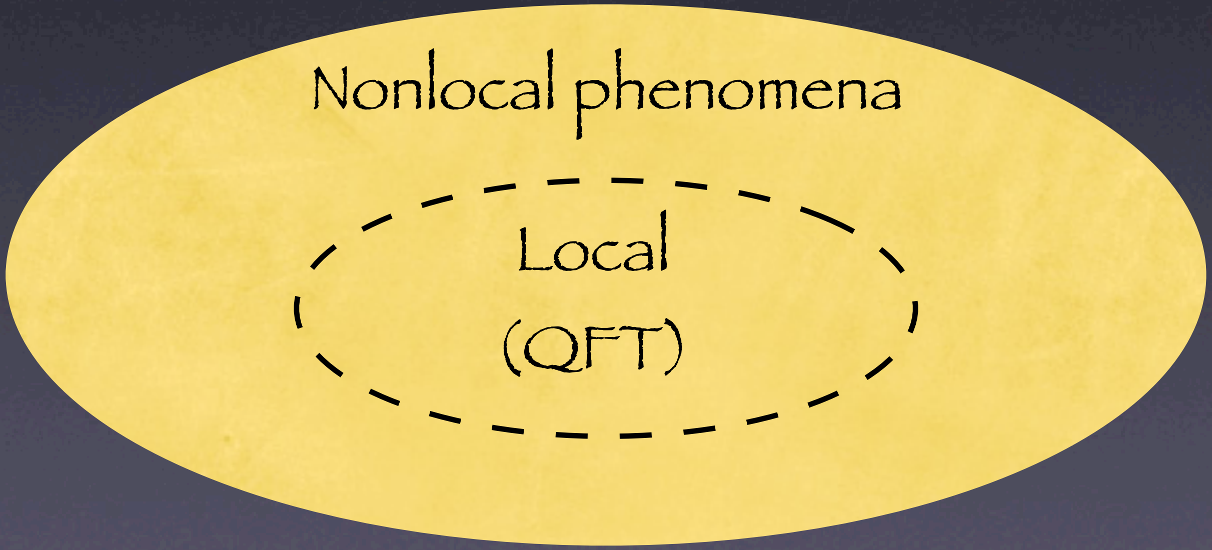
...

Some questions:

1) What is the mechanism for breakdown?

extendedness of strings (branes ...)?

2) What is the "correspondence boundary"?



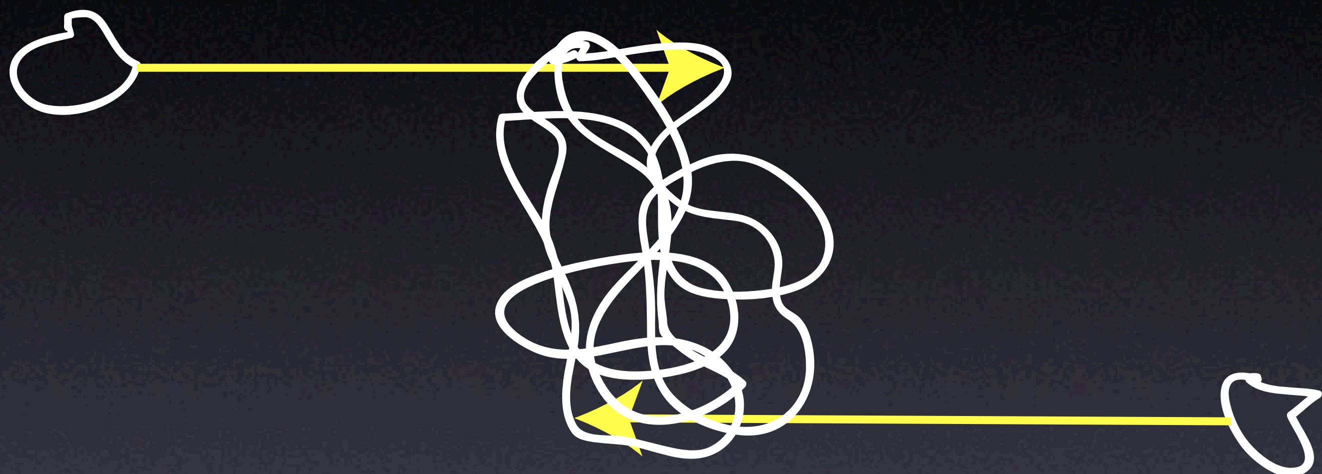
These questions are clearly related.

One way to address them is via high-energy scattering

(There's a related story more closely based on observables, etc.)

E.g. is the basic mechanism string extendedness?

Possible picture in HE scatt:



Long strings

$$L \sim E/M_s^2$$

$\longleftrightarrow$ String uncertainty principle

$$\Delta X \geq \frac{1}{\Delta p} + \alpha' \Delta p$$

(Veneziano, Gross)

($\longleftrightarrow$ nonlocality)

(Proposed app. to BH info: LPSTU)

What does this have to do w/BH formation?

Does it prevent? (Strominger, Gross)

Or is this BH formation? (~Susskind)

Let's investigate ...

Begin w/tree-level amplitude: high E

$$\mathcal{A}_0^{\rm string}(s,t) \propto g_s^2 \frac{\Gamma(-t/8)}{\Gamma(1+t/8)} s^{2+t/4} e^{2-t/4}$$

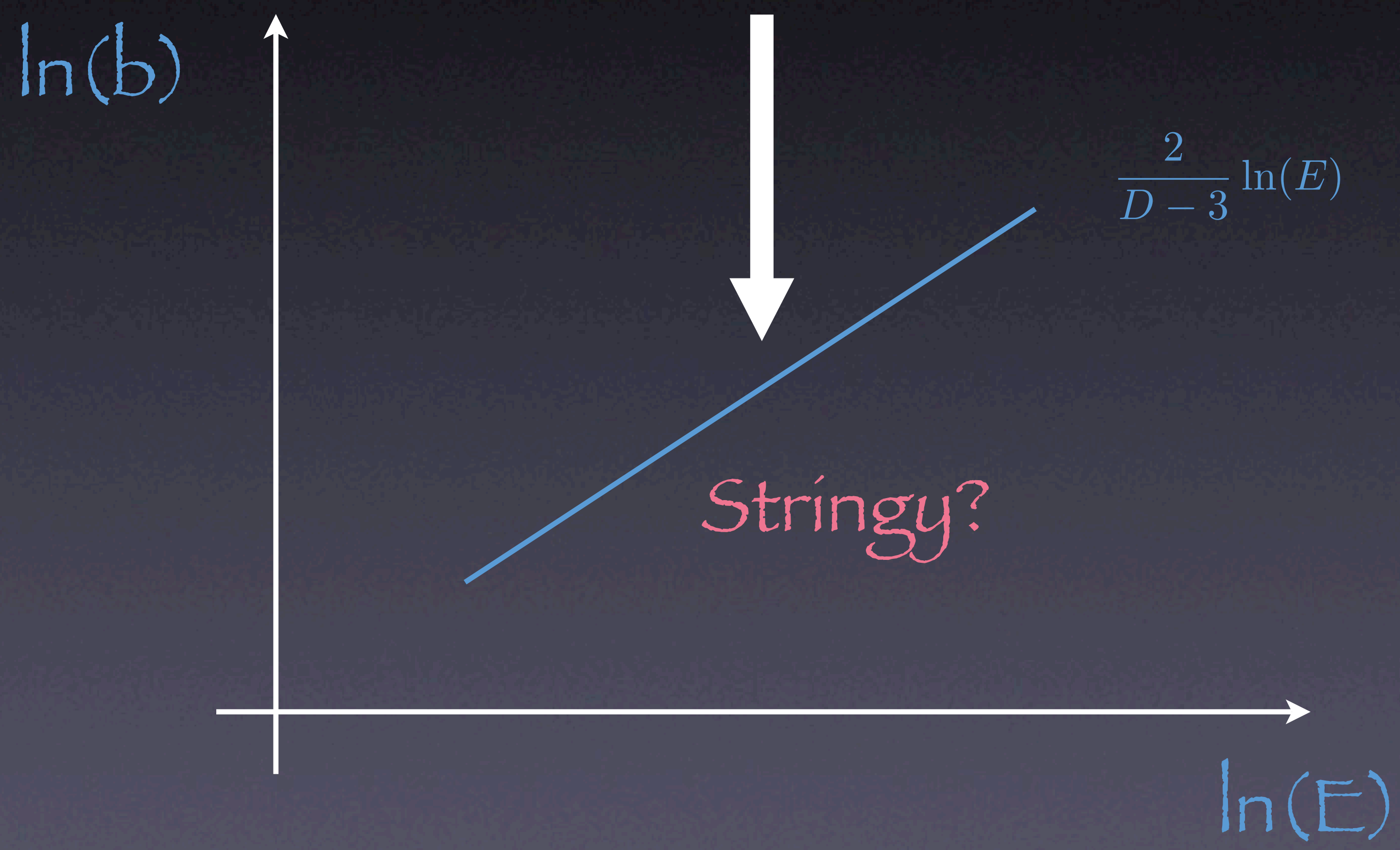
vs.

$$\mathcal{A}_0^{\rm grav}(s,t) \propto G_D \frac{s^2}{t}$$

- No evidence for long string effects;
- But significant modifications for $t \sim -1$

To investigate: (s,t) $\longrightarrow$ (E,b) $E \ggg M_P$

e.g. $t \sim -1 \Leftrightarrow b \sim E^{2/D-3}$ (D noncmpct dims)

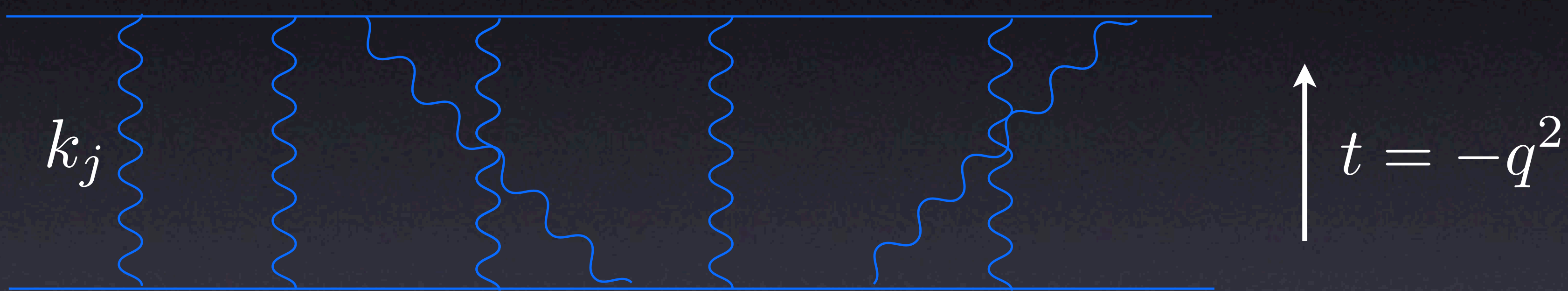


Fix E -- lower b

To check, include loops:

(Following Amati, Ciafaloni, Veneziano; Muzinich-Soldate; SBG, Gross, Maharana)

Ultrahigh-E: Eikonal



$$iA_N^{\rm string} = \frac{2s}{(N+1)!}\int \left[\prod_{j=1}^{N+1} \frac{d^{D-2}k_j}{(2\pi)^{D-2}} \frac{iA_0^{\rm string}(s,-k_j^2)}{2s}\right](2\pi)^{D-2}\delta^{D-2}\left(\sum_j k_j - q_\perp\right)$$

$$\prod_{j=1}^{N+1} \frac{E^{2-\alpha' k_j^2}}{k_j^2}$$

1) $k_j \approx q/(N+1)$

2) $E^{-\alpha' q^2/(N+1)}$

Thus at large N, string corrections get smaller

Which N dominates?

Can sum eikonal series:

$$iA_{\rm eik}(s,t) = 2s\int d^{D-2}\mathbf{b}\, e^{-iq_\perp\cdot\mathbf{b}}(e^{i\chi(b)}-1)$$

with $\chi(b) \sim G_D \dfrac{E^2}{b^{D-4}}$

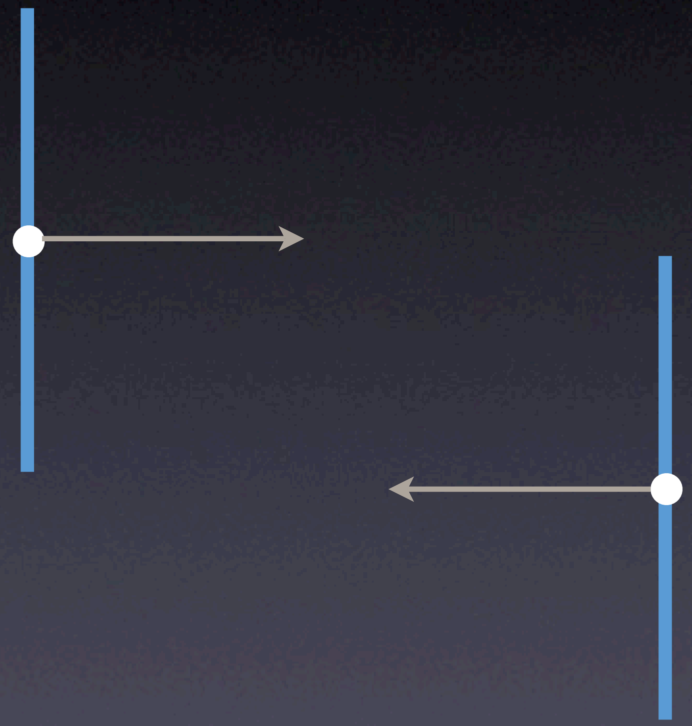
$\Leftrightarrow$ Dominant N: $N \sim \dfrac{G_D E^2}{b^{D-4}}$;

At $t \sim -1$: $N \sim (G_D E^2)^{\frac{1}{D-3}}$

$\therefore$ Large loop order dominates.

Eikonal ⟷ classical scattering

Two Aichelburg-Sexl shocks (ACV: checks)



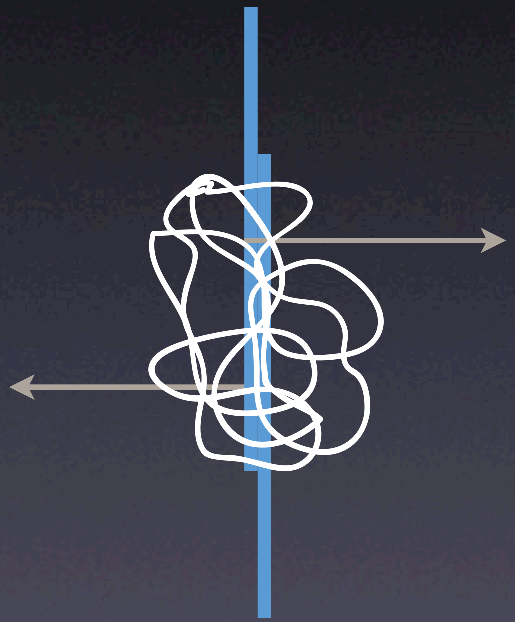
Black hole formation?

But - can excite strings: "diffractive excitation" (ACV)

Indeed, unexcited (elastic) amplitude, near Schwarzschild radius:

$$A_{el} \sim \exp\left\{-E^{(D-4)/(D-3)}\right\} \qquad !!$$

So:



??

No black hole??

Info carried away?

(Veneziano, 2004)

But there is a contrary intuition: string only "spreads out" "after" collision??

However, string spreading is a notoriously fuzzy concept...

Where is the string?

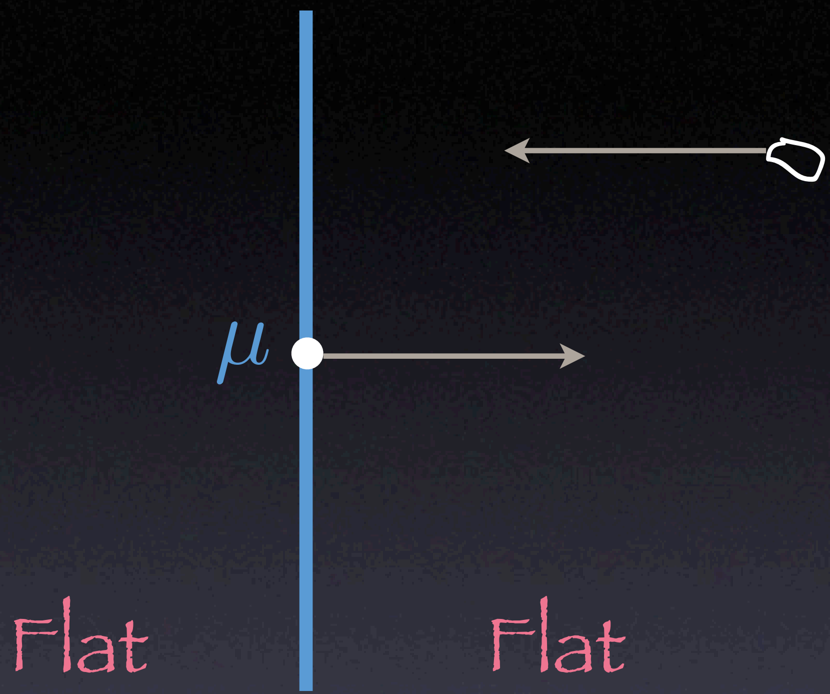
Karliner, Klebanov, Susskind: it depends

“low resolution”

“high resolution”

So: need to check for process in question ...

A test:



$$ds^2 = -du dv + dx^i dx^i + \Phi(\rho)\delta(u) du^2$$

$$\Phi(\rho) = -8G\mu \ln \rho \quad , \quad D = 4$$

$$\Phi(\rho) = \frac{16\pi G\mu}{\Omega_{D-3}(D-4)\rho^{D-4}} \quad , \quad D > 4$$

Scattering in a plane-wave metric:

de Vega and Sanchez; Horowitz and Steif

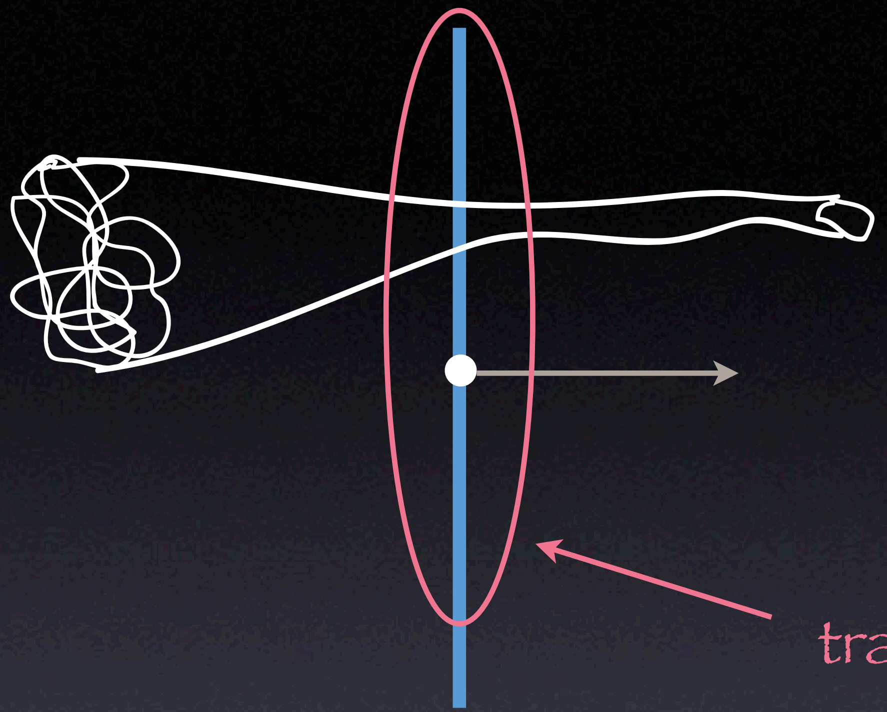
Light cone quantization

Compute for incoming unexcited string:

$$\langle \hat{X}^i_\epsilon(\tau,\sigma)\hat{X}^i_\epsilon(\tau,\sigma)\rangle$$

Where $\hat{X}^i_\epsilon(\tau,\sigma)$ is deviation from CM of string, w/world sheet regulator ϵ

Find:



Indeed, origin of effect is "tidal string excitation"

$$(\Delta X)^2 \sim |\ln \epsilon| + \left[\frac{G_D E^2}{b^{D-2}} \tau\right]^2 |\ln \tau| \qquad \epsilon \ll \tau$$

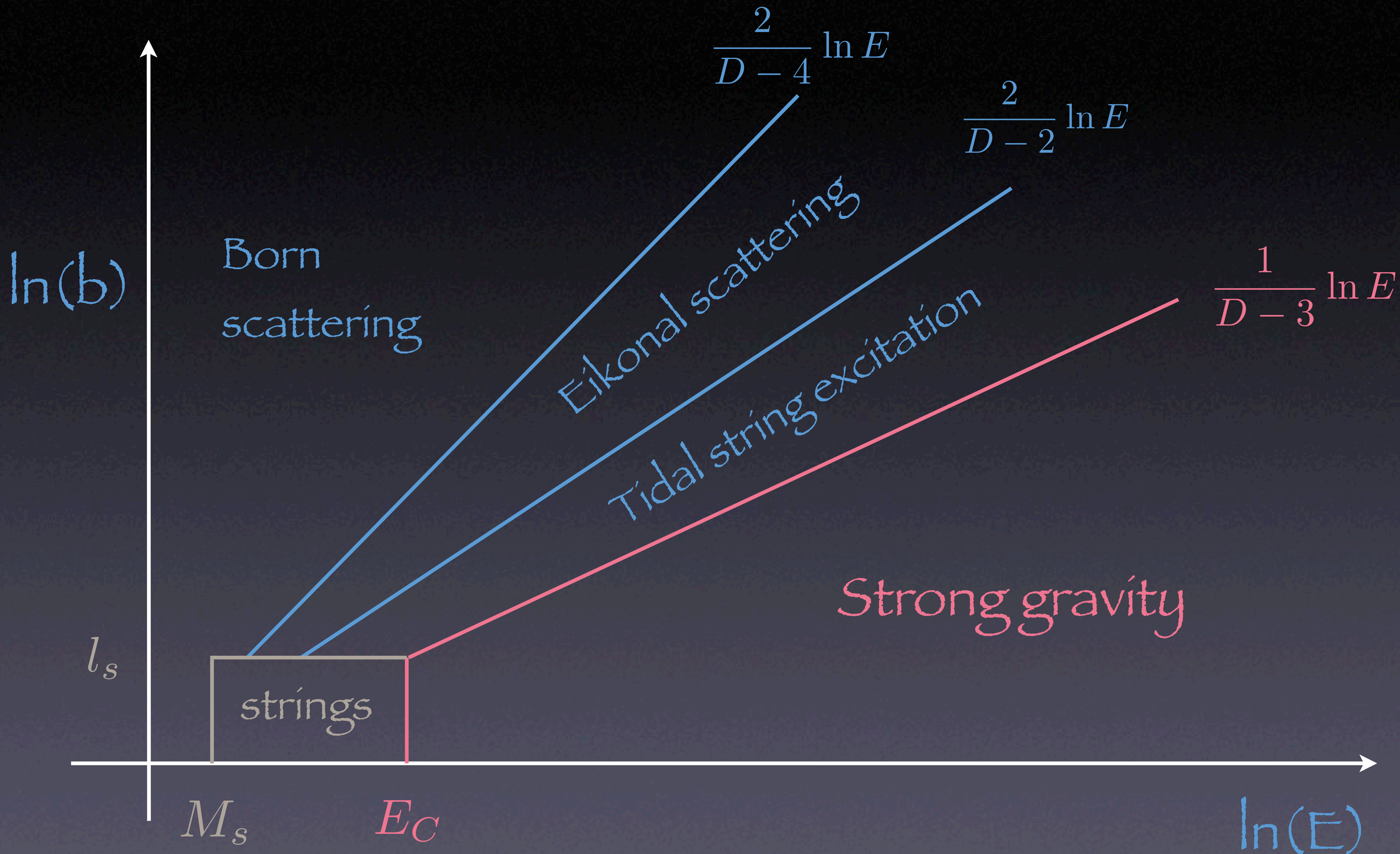
For small tau: inside trapped surface

Thus:

- String appears to behave ~locally during collision
- Trapped surface (aka black hole) appears to form

What conclusions can we draw?

1. A suggested "phase diagram:"



2. Perturbation thy apparently breaks down

$$1 \quad + \quad \mathcal{O}\left[(R_S(E)/b)^{D-3}\right]$$

...not short distance

This is a challenge to string calculability ...
(AdS/CFT)

3. Mechanism: no apparent fundamental role for string extendedness

A. Assuming scattering is finite and unitary:

unitarization apparently via intrinsically nonperturbative gravitational effects?

B. This dynamics is probably not local.

A possible "principle:" the nonperturbative physics that unitarizes gravity in domains where gravitational perturbation theory fails is nonlocal

4. Suggested correspondence boundary:

where does GR+LQFT break down?

2 part Fock sp.: $\phi_{x,p}\phi_{y,q}|0\rangle$

(min uncertainty wavepackets)

good description for $|x-y|^{D-3} > G|p+q|$

where $G \sim G_{Newton}$

"the locality bound"

(extends off shell?)

How does this relate to BH info?

Criteria/evidence for locality vs. nonlocality?

What can one say about cosmology?

What does AdS/CFT say?

...

Criteria for locality, and breakdown

1. Derivable from local QFT

2. $[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 \;, \;\; (x-y)^2 > 0$

3. Bounds/analyticity: Froissart; Cerulus-Martin; polynomial boundedness ...

2. $[\mathcal{O}_1(x), \mathcal{O}_2(y)] = 0 \ , \ (x-y)^2 > 0$

- There are no local gauge invariant observables in gravity. (Diffeos!)
- One can construct gauge invariant "proto-local" observables that approximately reduce to local observables in certain states (SBG, Marolf, and Hartle hep-th/0512200; Gary and SBG, hep-th/0612191).
- However, in situations characterized by the locality bound (and generalizations), one encounters obstacles to such a reduction.
- Thus this criterion for locality apparently is only approximate and appears to break down in situations of interest.

3. Bounds/analyticity: Froissart; Cerulus-Martin; polynomial boundedness ...

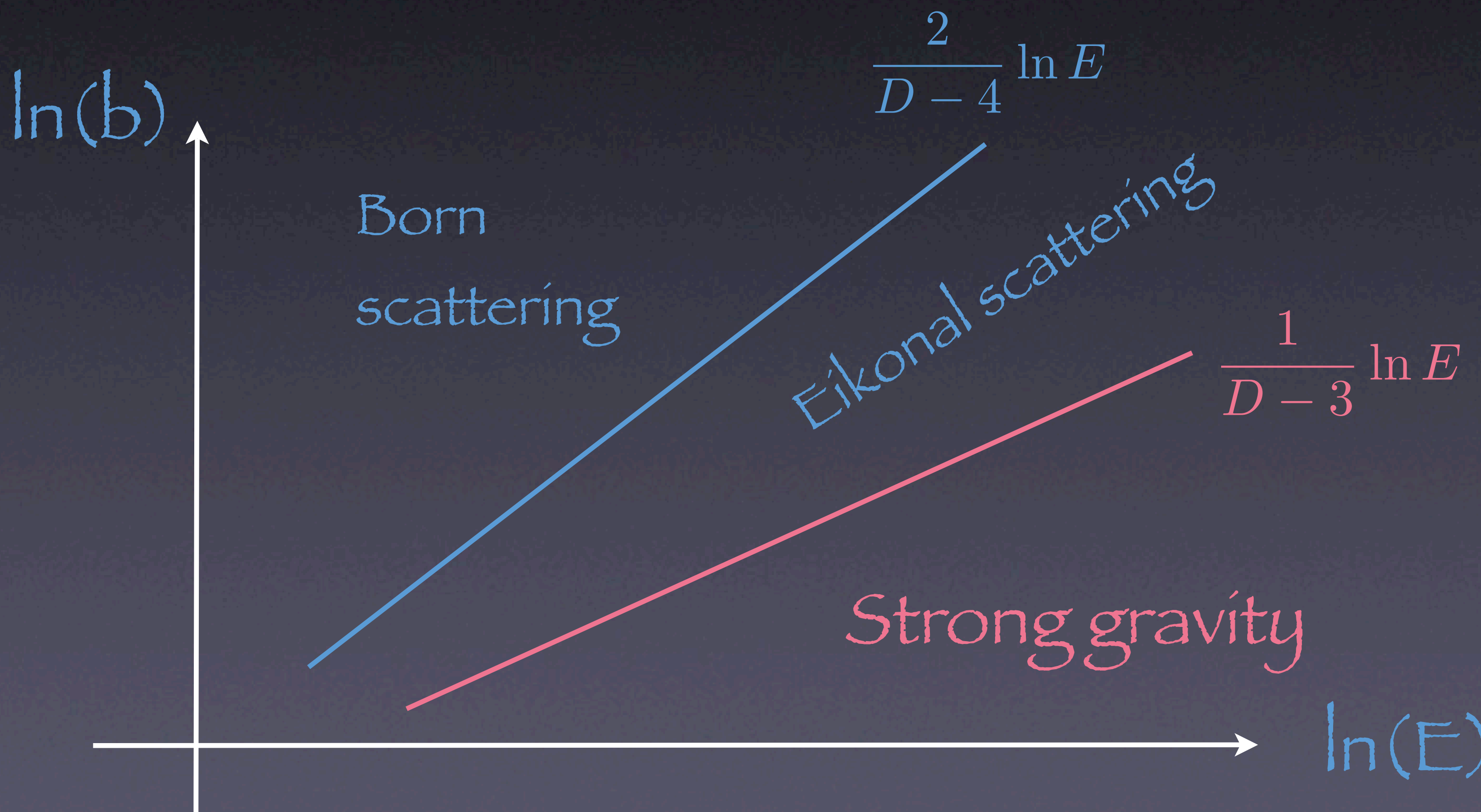
What general properties of gravitational amplitudes can we infer?

(WIP w/ M. Srednicki)

E.g. study partial wave expansion of 2-2 scattering (IR: D>6)

$$T(s,t) = (const)E^{4-D}\sum_{l=0}^{\infty}(l+\nu)C_l^{\nu}(\cos\theta)\left[e^{2i\delta_l(s)-2\beta_l(s)}-1\right]$$

$$\nu = \frac{D-3}{2}$$



Some features:

A. Understand Born, eikonal regions

e.g. $\delta_l \approx [ER_S(E)]^{D-3}/l^{D-4} \quad , \quad \beta_l \approx 0$

B. Ansatz for BH region

$$\beta_l \approx \frac{S(E,l)}{4}$$

consequences (tentative)

- amplitudes apparently obey Cerulus Martin
  (contrary to earlier expectations)

- absorptive amplitude violates Froissart

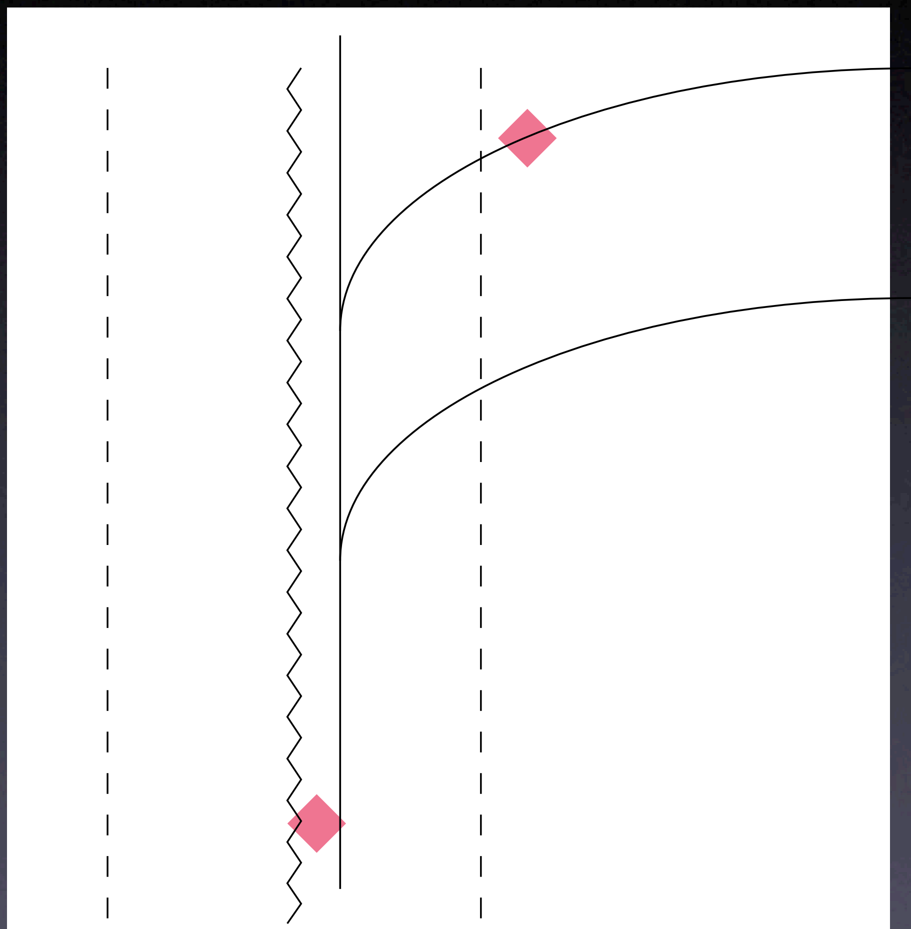
$$\sigma_{abs} \sim [R_S(E)]^{D-2}$$

- correspondingly, amplitudes not poly bdd:

$$T(s,t) \sim e^{R_S(E)\sqrt{t}}$$

(Not "local" by usual criterion)

What is missing in Hawking's argument for information loss?



proposal:

non-perturbative, non-local effects that become important by

$$T \sim R_S S_{BH}$$

(strong complementarity/ strong holography not needed?)

Some comments:

- there exists motivation for such effects, based on a) apparent breakdown of perturbation thy in nice slice quantization and b) limitations on observation of state. See hep-th/0703116

- a complete picture of how/why such physics enters and how it relays the information would require knowledge of this nonpert. dynamics ...

What does AdS/CFT (or matrix thy) say?

Commonly believed that one has complete nonpert descriptions of string theory

- AdS/CFT: need to extract flat space limit. Subtle. Concrete First test: can we see $1/q^2$ of Born regime? (WIP w/ M. Gary)

- Matrix thy: does it avoid divergences of grav. pert thy?

Cosmology: de Sitter, etc.

- if complementarity inessential in BHs, there should also be a global picture for dS.

- steps towards the formulation of such a picture:

SBG and Marolf, arXiv:0705.1178 and WIP

- some features: finite number of pert. dS states not violating loc. bd.; no recurrences; relational observation

- apparent limitations to local QFT description of global picture by timescale $R_{dS} S_{dS}$: Boltzmann brain observers; large perturbative corrections ~BH case ... (longer times likely allowed in static patch picture)

- related constraints found in Arkani-Hamed et al [arXiv:0704.1814] picture of regulating dS: large fluctuations at time $\sim R_{dS} S_{dS}$

Summary

- several considerations (HE scattering; observables; BH information, ...) support breakdown of conventional locality

- mechanism: no apparent role for string extendedness; rather nonperturbative gravity

- not clear how string theory addresses these issues

- correspondence boundary for such a "nonlocal mechanics:" locality bound, etc.

- such nonlocality could explain how info escapes black holes (“unitarity restored at the price of locality”)

- related story for inflationary cosmology; potentially places limitations on regime of local QFT description

(might we expect corresponding limitations on eternally inflating landscape?)